Near-Field Geodetic Study Of The San Andreas Fault

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TECHNICAL ABSTRACT

We surveyed sites of four small-aperture geodetic networks along the San Andreas fault in northern California. Our GPS measurements were combined with line lengths measured in the 1970s and 1980 by the US Geological Survey (USGS) to measure near-fault strain rates, averaged over a few km on either side of the fault. For three of the four networks, we found high near-fault strain rates (gamma1 = 0.8 microradian/yr), which could be explained by either a shallow (~5 km) seismogenic (locking) depth for the fault or a typical seismogenic depth of 10-15 km and a compliant layer a few km thick located along the fault. The fourth network had a strain rate about half that of the others, but was poorly fit by a uniform strain model, and the strain estimate may be unreliable. A similar network at Point Arena has a strain rate about 1/3 that of the networks studied here. We interpret the consistently high near-fault strain rates from the San Francisco peninsula north to Bodega Bay as being correlated with the presence of Salinian basement to the west of the fault.

NON-TECHNICAL ABSTRACT

We studied four geodetic networks along the San Andreas fault from the San Francisco peninsula in the south to Bodega bay in the north. We repeated earlier surveys at each network to extend the time span of data, and determined the strain rate for each network. For three of the four networks we found near-fault high strain rates, which indicate either that the fault is locked near the surface but slipping steadily below about 5 km depth. At Point Arena to the north of these networks, the near-fault strain rate is about 1/3 as high, which can be explained if the fault is locked near the surface and slipping below about 15 km depth, a much more typical result. An alternative explanation for the high near-fault strain rates from the Peninsula to Bodega Bay is that there is a narrow layer of material located in the fault zone with different elastic properties

than the surrounding rock. We interpret the consistently high near-fault strain rates from the San Francisco peninsula north to Bodega Bay as being correlated with the presence of Salinian basement to the west of the fault.

Investigations Undertaken

In the course of this project we made GPS measurements at sites in four small-aperture geodetic networks along the San Andreas fault in northern California (Figure 1). These networks were established by the US Geological Survey (USGS) in the 1970s and early 1980s, and most had not been surveyed since the mid-1980s. The networks typically span about 5 kilometers on either side of the surface trace of the fault. Line length rates of change from these networks were used to measure the near-fault strain rate at the fault, and to distinguish between shallow or deep locking depths. The combined line length and GPS data is sufficient to determine the rates of change of line lengths with a precision of better than 1 mm/yr. With this data we address two important questions: (1) Is there systematic variation along strike in the near-fault strain rate? Variations along strike could be explained by spatial changes in the depth to which the fault is locked in the interseismic period, or by variations in the elastic properties of rocks near the fault zone. (2) How well can a single elastic model fit both the near-field and far-filed strain observed geodetically? In future work we will cooperate with Roland Bürgmann of UC Berkeley to develop a three dimensional elastic model (or a series of two dimensional models) to explain both the near field data and the existing far-field data, and expect that this data will improve our knowledge of current slip rates on the major strike-slip faults in the Bay Area.

Work on this project began in May 1996 with site reconnaissance. Most of the site reconnaissance was completed in May and October 1996, along with part of the fieldwork. GPS fieldwork was completed in April 1997, and all GPS data were then analyzed. Detailed reprocessing of the EDM data, combination of the EDM and GPS data, and analysis of the strain derived measured by the networks was completed in late 1997 and early 1998.

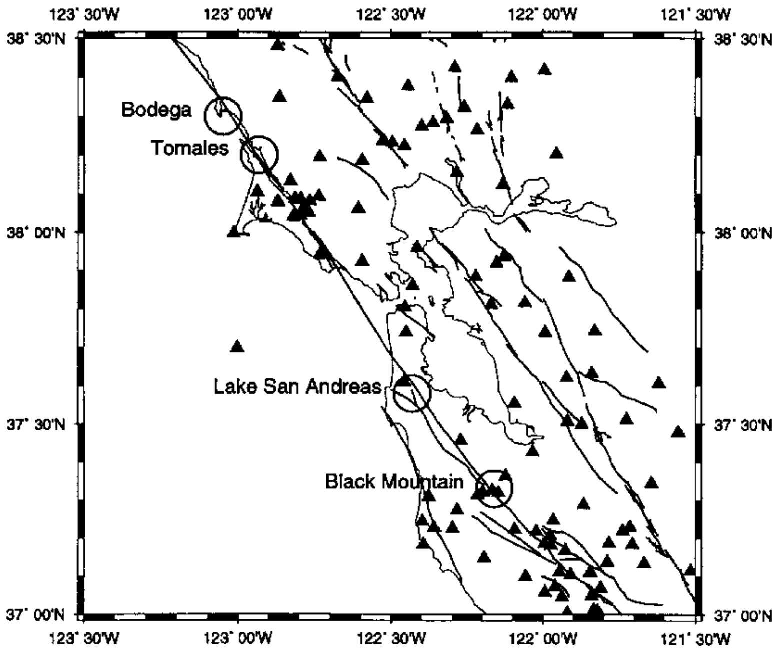

Figure 1. Locations of the small networks being studied in this project. Small black triangles show the locations of regional geodetic sites. Blowups of the two southern networks are shown in Figure 2, and the Bodega and Tomales networks in Figure 3.

Site Reconnaissance

Because many of the sites needed for this study had not been visited for up to a decade, a significant effort in field reconnaissance was required. The main part of the field reconnaissance was carried out in May 1996, with some additional sites found in October 1996 and April 1997. Existing descriptions for many sites were poorly written or out of date, and markers were found buried under as much as a foot of soil. An appendix to this report contains a complete set of new descriptions for all of the sites used in this study, including up-to-date contacts and permitting info for all sites (Appendix 1).

The great majority of sites were found in good condition, although many had been buried. Because the descriptions as written generally omitted mention of nearby points of reference, considerable time was spent searching for markers with a metal detector. A few markers have not yet been found, and may be unrecoverable. In some cases we found sites by surveying temporary markers in the probable vicinity of each of the missing marks, and inferring offsets between the temporary marks and the missing survey markers from the GPS coordinate solutions. With the exception of a few sites that clearly have been destroyed, the missing sites are almost certainly buried rather than destroyed; however, from the information available about the missing sites it seems unlikely that they will ever be found except through blind luck.

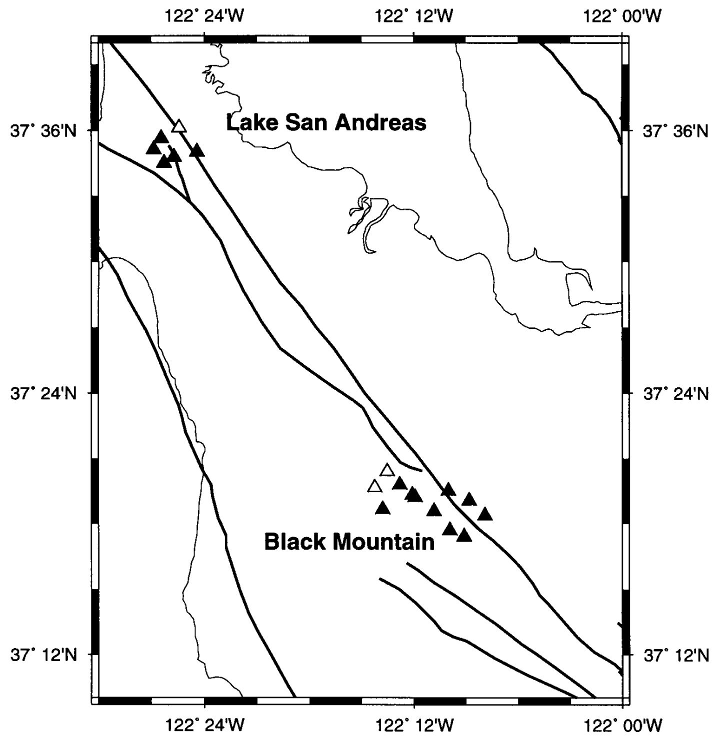

Figure 2.The Black Mountain and Lake San Andreas networks. Solid triangles show sites surveyed with GPS during the course of this project. Open triangles show EDM sites that were not found.

Black Mountain/Radio Facility Network

The Black Mountain/Radio Facility network is the southernmost network in this project (Figure 2), located on the San Francisco peninsula overlooking Palo Alto. One site in the network was destroyed in the 1980s, and a second site could not be visited because the owners could not be contacted to obtain permission. No description could be found for a third site. In addition to the nearly complete occupation of this network, we made simultaneous occupations at several nearby sites that are part of a larger-scale GPS networks. Using these measurements, plus data from two of the Black Mountain network sites that are part of the larger-scale Black Mountain profile, it will be possible to determine vector velocities for all sites in the Black Mountain network, although we have not yet done this.

Most lines in the Black Mountain network were surveyed regularly before 1982, then again in 1989, shortly before the Loma Prieta earthquake. The lines were surveyed one or two times immediately after the earthquake. Line length changes in the five to seven years since the last EDM survey range from near zero to about 30 millimeters. For three lines, the comparison of the GPS and EDM results for the Black Mountain network is clouded by large (>1 meter) discrepancies, which can be explained if a reference mark was used in the EDM surveys. The existing documentation and memories of USGS personnel were not clear on this matter. The lines with large discrepancies were excluded from further consideration, but will be rechecked when we have a chance to visit the sites in the field again.

Lake San Andreas Network

The Lake San Andreas network is located on the San Francisco peninsula at the Lake San Andreas reservoir (Figure 2). Of the six sites in the network, five were found and occupied. One site was not found and one had clearly been destroyed.

Tomales Bay Network

The Tomales Bay network (Figure 3) is located on the shores of Tomales Bay, which separates the Point Reyes Peninsula from the mainland. The San Andreas fault runs along the length of Tomales Bay. One site in this network could not be found, because no description had ever been written for it, nor were any precise coordinates available. Ironically, this site was installed after the USGS field crew in 1983 had been unable to locate a historic triangulation marker on the same hill.

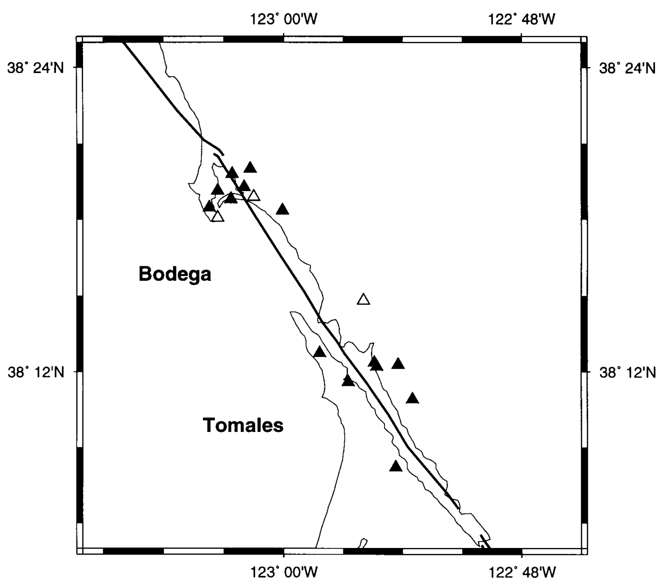

Figure 3.The Tomales and Bodega networks. Solid triangles show sites surveyed with GPS during the course of this project. Open triangles show EDM sites that were not found.

Bodega Bay Network

The Bodega Bay network (Figure 3) is located around Bodega Bay, north of the Point Reyes peninsula. The San Andreas fault runs through Bodega Bay. One site in the network was destroyed in the 1970s when housing development/gold course was built; of the other sites, all but one were found. It should be possible to find the site that was not found (FINBACK), although we were unable to do so despite several trips and even after measuring a temporary mark. While it could have been destroyed, it seems more likely that it was simply buried. The Bodega network was surveyed many times with EDM, beginning in 1967. This network was compromised more than the others by the loss of benchmarks. Most remaining lines surveyed with GPS were at high-angles to the fault.

Results

1. Analysis of GPS data

We analyzed all data presented in this paper using the GIPSY/OASIS II software (release 4) developed at the Jet Propulsion Laboratory (JPL) *[Zumberge et al.*, 1997; *Gregorius*, 1996]. We combined the local data with data from regional permanent sites, and estimated solutions while fixing JPL's fiducial-free orbit (estimated without significant *a priori* site position constraints). The solutions were then transformed into ITRF94 using daily transformation parameters provided by JPL. The GPS estimated line lengths for most lines have a precision of about 2 mm. The uncertainty in the GPS line length estimates is comparable to that of the EDM. GPS line lengths were increased by 0.44 ppm based on an empirical scale difference determined by the USGS

[Savage ref]. This scale difference, 0.44 mm per kilometer, amounts to no more than a few millimeters on any of the lines used.

2. *Analysis of the EDM data*

We carefully reanalyzed all of the EDM data to ensure consistency, since some of the networks were surveyed with a variety of instruments. The EDM data reduction programs were obtained from USGS, and recompiled and run on our computers. Considerable effort was required to so this, since there was no written documentation for the programs, and none of them actually compiled without modification. In addition, several programs were used at different times for different instruments or file formats, and there was no documentation explaining which program was to be used with which data. With the recompiled programs we were able to exactly reproduce the processed line length files provided to us by USGS.

We then evaluated the effect of coordinate errors in the EDM processing. EDM data reduction is not very sensitive to errors in the assumed a priori station coordinates, except for the corrections for tropospheric refraction. These corrections are sensitive to height errors, and could be important for short lines with significant height differences between the stations. Possible errors in computing tropospheric corrections had been suspected for the Tomales network. We reprocessed all of the EDM data using coordinates derived from our GPS solutions, and found that the mark-to-mark line lengths were identical with those computed using the original coordinates; however, the line lengths projected to horizontal were different in a few cases. The mark-to-mark line lengths were reduced to purely horizontal sea level arc distances, an assumption in the projection is that the line length changes reflect purely horizontal motions. Since the line lengths do not change by very much over time, the projected line length changes are not affected much by errors in the assumed coordinates as long as the same heights were used for reducing all observations. Because it was more convenient to reduce the GPS line lengths to sea level arc distances using the GPS coordinates, we used the EDM lines processed using GPS coordinates. The height is the most critical component of the coordinates.

Several lines in the Lake San Andreas network were found to be very sensitive to errors in the coordinates that had been assumed in the original USGS processing. One example is the line from ERC1 to ERC2, a 1200 meter line with an elevation difference of about 200 meters. For a short, steep line, the projection of the line to horizontal is very sensitive to errors in the relative station heights. For this line, the USGS and our GPS coordinates differed by about 40 meters in height, a consequence of the USGS coordinates having been estimated from a map. The mark-to-mark distances were largely the same regardless of the coordinates used, but the horizontal sea level arc distances changed by up to 10 cm depending on the coordinates used. As a result, we reprocessed all EDM data using coordinates derived from the GPS solutions.

3. *Strain rates*

We used a simple linear fit to estimate the line length rates of change for each line using the GPS and EDM data, and then estimated strain rates for each network from the set of line length rates of change. In a few cases we found large (>1 meter) discrepancies between the GPS and EDM line lengths. Most likely, these discrepancies result from different marks having been used for the GPS and EDM measurements. It was common with EDM networks to use more than one nearby marker at a site because of line-of-sight restrictions. Line length rates of change were then converted to strain rates, and the best-fitting uniform 2D strain tensor was found for each network.

Table 1. Strain Rates. The tensor strain rates $e_{1,1}$, $e_{1,2}$ and $e_{2,2}$ are estimated from the observed line length rates of change. The three parameters γ_1 and γ_2 (shears) and Δ (areal dilatation) are an equivalent representation of the strain. Units for tensor shears and the areal dilatation are 10^{-6} yr^{-1}, and units for the engineering shears are 10^{-6} rad yr^{-1}.The reduced chi-squared statistic, χ_ν^2, is also given. If the uncertainties are realistic, χ_ν^2 should be equal to 1.0.

		Tensor Shears			Engineering Shears			
Network	lines	$e_{1,1}$	$e_{1,2}$	$e_{2,2}$	γ_1	γ_2	Δ	χ_ν^2
Black Mt	19	0.51 ± 0.04	-0.07 ± 0.04	-0.29 ± 0.04	0.81 ± 0.05	-0.13 ± 0.07	0.22 ± 0.06	2.43
L. San Andreas	7	0.40 ± 0.04	0.16 ± 0.04	-0.28 ± 0.08	0.68 ± 0.08	0.31 ± 0.09	0.11 ± 0.09	1.21
Tomales	14	0.07 ± 0.01	0.19 ± 0.3	-0.28 ± 0.03	0.35 ± 0.03	0.38 ± 0.06	-0.21 ± 0.03	13.3
Bodega	8	0.20 ± 0.16	-0.11 ± 0.10	-0.63 ± 0.10	0.84 ± 0.17	-0.22 ± 0.21	-0.44 ± 0.22	1.78

Strain rates for each network are summarized in Table 1. The engineering shear strain γ_1 corresponds to right lateral shear on a plane striking N45°W, which is rotated only 10-15° from the orientation of the San Andreas fault. As expected, for three of the four of the networks γ_1 is the dominant strain component. With the exception of the Tomales network for which several lines are poorly fit by a uniform strain model, γ_1 is relatively constant for all networks with a typical value of 0.8 microradian/year. Such a value is comparable to that observed at Point Reyes (Lisowski et al., 1991). The Tomales network appears to be an outlier because of the high misfit, and we are not sure why the strain rate is so different for that network compared to Pointe Reyes immediately to the south and Bodega Bay immediately to the north. A first-order conclusion is that all of the EDM networks from the San Francisco peninsula north to Bodega Bay exhibit high near-fault strain rates, which are roughly a factor of 3 greater than the strain rate averaged over larger areas (Lisowski et al., 1991). North of Bodega Bay, however, the situation is quite different. GPS measurements and a reoccupation of the near-fault EDM network at Point Arena found a much smaller near-fault strain rate, about 1/3 of the rates found for the networks considered in this study (Freymueller et al., in press).

Elastic dislocation models predict that the maximum strain rate will be found at the fault, and in the case of a two-dimensional (infinitely long) strike slip fault the maximum shear strain rate is a simple function of the fault slip rate and locking depth (e.g., Savage and Burford, 1973). The near-fault strain rate can then be used to estimate the locking depth of the fault, assuming that the slip rate and elastic properties are known. The locking depth is assumed to be equivalent to the depth to the base of the seismogenic zone, and little if any coseismic slip would occur below the locking depth since below that depth stress is relieved through ductile or plastic deformation. If a uniform elastic half-space is assumed, the locking depth of the San Andreas fault was estimated to be only 5 km for the Point Reyes data, and equivalent values are estimated for all but the Tomales network. A locking depth of about 10 km is preferred for the Tomales network. An alternate model, suggested by Lisowski et al. (1991), calls on lateral inhomogeneities in the elastic properties of the earth to explain the high near-fault strain rates. If the fault zone itself contains material that is significantly more compliant than the surrounding material, strain will be concentrated in the layer of more-compliant material (Rybicki and Kasahara, 1977).

Discussion

High near-fault strain rates are found between the San Francisco peninsula and Bodega Bay, with the possible exception of Tomales Bay, but the near-fault strain rate further to the north at Point Arena is relatively low. Multiple interpretations of these results are possible. High near-fault strain rates could be due to either the presence of a compliant near-fault zone, or to a shallow locking depth. A lower near-fault strain rate could be due to the absence of a compliant near-fault zone, or to a deeper locking depth. Note that in one case we ascribe the along-strike strain rate variations to variations in locking depth with constant elastic properties, and in the other case to variations in the elastic properties with a constant locking depth. At this point, we cannot distinguish between these two alternatives, although they have very different implications for seismic potential, since the seismic moment potentially available for release scales with the locking depth.

In either interpretation, between Bodega Bay and Point Arena there is either a significant change in the depth to the base of the seismogenic zone, or a significant reduction in the thickness of (or elimination of) a near-fault layer of compliant material. Two plausible explanations for such a change are the maturity of the fault zone (in the south the fault is older than in the north and has slipped a greater distance), or a change in the material properties of the rocks on either side (granitic Salinian basement is found west of the San Andreas fault as far north as Bodega Bay, but is not found further north; Franciscan melange is found east of the fault over the entire area).

We prefer the interpretation that a change in material properties is responsible for the change in near-fault strain rates and locking depths. It is reasonable to suppose that the thickness of a compliant layer near the fault would increase as the fault became older and had undergone greater slip. Unless there is a critical time at which such a layer rapidly forms, we would expect to see a steady increase in the near-fault slip rate from north to south, which is not observed. Instead, we observe an essentially constant near-fault strain rate with a sudden drop north of Bodega Bay. This argues for a change in the material properties, associated with the presence of the Salinian basement to the west of the fault. Here we assume that the strain estimate for Tomales Bay is unreliable due to the extremely high misfit.

Another, more speculative, alternate hypothesis can be formed if we assume that the large misfit for the Tomales network is not due to measurement error, but instead reflects real variations in the strain within the network. During the 1906 earthquake, slip in Tomales Bay was 6-8 meters, 50-100% greater than in the surrounding areas, as determined both by measured surface offsets (Lawson, 1908) and inversion of triangulation data (Thatcher et al., 1997). Thatcher et al. (1997) assumed a constant seismogenic depth of 10 km for the entire fault; if there were significant variations in seismogenic depth within the span of Tomales Bay, constant slip on the fault would be manifested in the geodetic inversion as a variation in slip along strike, with the highest slip being found where the actual seismogenic depth was largest. Such a variation would result in non-uniform strain within the network and a poor fit for a single strain tensor. Because the Tomales network was measured only once with EDM, and a critical site in the north was lost, we have not separated the network into northern and southern parts to test this hypothesis.

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